ISSN 1995-4255, Contemporary Problems of Ecology, 2022, Vol. 15, No. 7, pp. 806–816. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2022, published in Lesovedenie, 2022, No. 3, pp. 321–334.

Impact of Natural Climate Factors on Mechanical Stability and Failure Rate in Silver Birch Trees in the City of Donetsk

V. O. Korniyenko[a], * and **V. N. Kalaev**[b]

[a] *Donetsk National University, Donetsk, 83001 Ukraine*
[b] *Voronezh State University, Voronezh, 394018 Russia*
**e-mail: kornienkovo@mail.ru*

Received July 13, 2020; revised December 7, 2020; accepted December 1, 2021

Abstract—A survey has revealed a relationship between the temperature factor and the biomechanical parameters (the modulus of elasticity) for wood tissues in the silver birch tree (*Betula pendula* Roth). At thawing temperatures, the elastic modulus decreases, on average, 2–2.5 times. A decrease of this kind is uneven, gradual. The rate of elastic-modulus change relative to the rate of woody-plant specimen/trunk thawing has the greatest effect on the mechanical stability of a tree. During thawing, the mechanical stability parameters tend to fall by 45%, on average. These changes affect the angles of divergence from the vertical axis of the trunk portions, the angles of its skeletal branch attachment, bending strength, and tree resistance to wind and gravity loads. Under a low anthropogenic impact, the bending stiffness value for plants at the age of 40–45 years is 22 ± 2% higher than that under the higher anthropogenic load in a city. Under the impact of anthropogenic load affected by the impact of wind loads, temperatures, and the other factors affecting weather, the transformation of architectonics of the silver birch crown occurs, which can cause irreversible deformations or trunk breakage under a blizzard and freezing rain. Therefore, 63 trees were uprooted and 168 woody plants underwent irreversible deformation, causing a high failure rate on the experimental plots in Donetsk from 2014 to 2020. Splits were recorded in plants at heights of 2–4 m (35%), 5–6 m (17%), 7–8 m (52%), and 9 m (6%). Correlation analysis revealed a strong positive relationship between the L : D morphometric coefficient (trunk length-to-diameter ratio) and the mechanical stability ($R = 0.87$), along with the failure rate ($R = 0.79$) of silver birch trees. In this regard, it seems possible to use the L : D coefficient as a morphometric marker for mechanical stability in silver birch trees in the south of the East European Plain (Donetsk Hill Ridge).

Keywords: Betula pendula Roth, silver birch, mechanical stability, failure rate, temperature, freezing rain, urban environment, urban plantations

DOI: 10.1134/S1995425522070150

INTRODUCTION

The ecosystem-based adaptation of woody plants to the impact of natural climate factors in urban environments is one of the most important challenges of functional ecology (Fournier et al., 2013; Dahle et al., 2017). The surveys are actively performed to assess the mechanical stability and the failure rates in trees under the effects of air temperatures (Green et al., 1999; Szmutku et al., 2011; Kornienko and Netsvetov, 2013; Kornienko et al., 2018), wind loads (James et al., 2006; Dahle and Grabosky, 2010; James et al., 2014; Dahle et al., 2017; Jelonek et al., 2019), and snow and ice storms (Nock et al., 2016). Many authors indicate the importance of studying the effects of snow and ice storms and wind loads on the ecosystem structure and function (Fahey et al., 2020; Klein et al., 2020) to assess the intensity and frequency of disturbances caused by natural climate factors, such as those indicated above (Curtis and Gough, 2018).

The wood moisture content affects the mechanical stability of woody plants, their modulus of elasticity, and the wood density (Green et al., 1999; Szmutku et al., 2011; Kornienko and Netsvetov, 2013). Most research papers concern surveys performed with samples of wood of a 12% moister content (industrial wood) (Zelinka et al., 2007; *Wood handbook*..., 1999, 2010; Virot et al., 2016). Only certain papers indicated the analyzed specimens with a moisture content of 145% (Mishiru, Asano, 1984a, b; Green et al., 1999, Shmytku et al., 2012; Spatz, Pfisterer, 2013; Nocetti et al., 2015), which corresponds to the special storage and operating conditions for woody materials. The green timber moisture content varies within 25(30)–225%, depending on the species (Niklas and Spatz, 2010). Seasonal dynamics of environmental factors and plant physiological parameters (transition from dormancy through vegetative stages) have effects on the moisture content in plant tissues. The range of wood moister-content variation is related to the rate of moisture desorption/sorption, which tends to reduce along with increases in the density of tissues and their contents of extractives (Sell, 1989). In addition, the parameters determining the response stability of a whole tree or its parts to the climate factors are associated with the wood moisture content. Therefore, it is incorrect to use the values produced for industrial wood in estimating living tree stability (Razdorsky 1955; Burgert et al., 2001). Some research papers (Virot et al., 2016) providing data on dry (industrial) wood for modeling the tree-stand behavior in relation to the impact of natural climate factors have to deal with critiques of science (Albrecht et al., 2016). Therefore, they are reduced to an idealized model which cannot be used to forecast tree planting.

It may be added that most of the research papers mentioned above are focused on surveys for studying the forests (natural tree stands). In addition, research on the mechanical stability of tree stands in urban environments (urban plantations) is scanty. Thus, M.V. Netsvetov et al. (Netsvetov et al., 2009; Kornienko et al., 2009; Netsvetov and Suslova, 2009) studied the mechanical response stability of woody plants in southeastern Ukraine to the vibration and acoustic impact of technogenic loads. These investigations are fundamental and legitimate for vibration ecology issues. However, the physicomechanical properties of tree tissues taken from the collection of the Donetsk Botanical Garden were studied only within the arboretum (a zone of low anthropogenic load). The values for the wood biomechanical parameters, including mechanical stability, may be different under the impact of anthopogenic factors (Dahle et al., 2017). Therefore, studying the physicomechanical properties of woody plant tissues in urban environments to test their mechanical stability and failure rates under the total impact of anthopogenic factors seems most important.

The objective of this survey is to assess the impact of natural climate factors and anthropogenic loads on silver birch trees in the south of the East European Plain (Donetsk Hill Ridge) with the Donetsk urban tree stands based on the generalized results taken from studies in 2014–2020.

The survey tasks involved (1) studying the temperature impact on silver birch woody-tissue elastic modulus in vitro (laboratory analyses), (2) assessing mechanical stability in silver birch in technogenic environments and the risks under temperature variations, (3) analyzing the natural-climate factor impacts on silver birch allometry in Donetsk urban plantations, and (4) evaluating the natural-climate factor impact on silver birch failure rates.

EXPERIMENTAL

The silver birch (*Betula pendula* Roth) was chosen as the object of the survey. According to open data, it is a species of high adaptive potential subjected to industrial pollution (Neverova et al., 2013); i.e., the species adaptive responses to extreme environments are complex. The silver birch values for membrane permeability as an integral parameter for plant-tissue functional status are low under the anthropogenic impact in urban environments. This can indicate both a high tolerance to air pollution and better functions of regulation and homeostasis systems when compared with other analyzed species in urban environments (Sarbaeva et al., 2023). With respect to the level of tolerance to high temperatures, hot dry winds, and the water-holding capacity, the species is considered medium resistant (Mikheeva et al., 2011).

The proportion of species in the urban plant species composition in the central part of modern Donetsk makes up approximately 5% (Suslova et al., 2012, Glukhov et al., 2016), while it comprises approximately 2% of all woody plants across the whole city (Polyakov, 2009). A tree age of 50 is considered critical in urban environments (Kornienko and Kalaev, 2018). This plant species is fast growing, frost- and drought-resistant, and undemanding in terms of soils. It is used in solitary, group, and alley plantations in the environments of the city of Donetsk. Silver birch is used in the first and second rows along the highways.

Further profound surveys are required, taking into consideration that there is not much research of this kind. This especially concerns issues urgent for basic and applied science related to the impact of the natural-climate factor on mechanical stability, structural and functional organization, and the adaptation of silver birch in transformed environments (the Donetsk Hill Ridge on the southern East European Plain).

Three land sites (plots 1–4) were chosen to perform the surveys. The length and width of the silver birch tree stand on plot 1 comprise approximately 385 and 50 m, respectively (the intersection of Leninskii prospekt and Odesskaya ulitsa). The trees were planted in 7 rows of 112 ± 3 birch trees each 2–3 m apart. The tree age is approximately 45 years. With respect to plot no. 2 (Kovanye Figury Park, the intersection of main streets such as ul. Artyoma and ul. Universitetskaya and pr. Vatutina and pr. Mira), the trees were planted as solitary trees grown along the footpaths. The age is 7–20 years. On plot 3 (pr. Ilyicha), the trees grow in linear plantations along roadsides. The age is 40–50 years. Plot 4 (Donetsk Botanical Garden, Arboretum) represents the southern woodland. The trees are planted along the avenue Makeevskoe shosse. The tree age is 40–50 years. The plants grow as solitary trees, in clumps or small groups of trees (3–5 units).

The intensity of road traffic as an anthropogenic load in the area was estimated for testing plots. It was revealed that, on plots 1–3, passenger cars (on average, 800–1000 units per h^{-1}), predominantly foreign-made vehicles, were the prevalent modes of transport.

Table 1. Parameter values for the anthropogenic load of auto transport and vibration-acoustic impacts

Plot number	Movement intensity, units per h^{-1} $\overline{x} \pm s_x$	Vibration and acoustic noise, dBA					
		near the road (curb)		1st tree line		edge of the tree stand	
		$\overline{x} \pm s_x$	MAX	$\overline{x} \pm s_x$	MAX	$\overline{x} \pm s_x$	MAX
1	1060 ± 54	78 ± 5	92	74 ± 2	80	69 ± 1	73
2	1681 ± 211	79 ± 4	110	76 ± 2	85	62 ± 5	68
3	1334 ± 30	79 ± 1	86	73 ± 1	79	68 ± 1	73
4	–	45 ± 5*					

* Natural sounds in plant stands.

Figs. 1–4 shows $\overline{x} \pm s_x$ denoting the average value ± standard deviation.

Table 2. Values for toxic soil and air substances in the land area in which the surveys were conducted

Plot number	Soil pollution, $\overline{x} \pm s_x$			Air pollution, $\overline{x} \pm s_x$		
	Zn, mg kg^{-1}	Cu, mg kg^{-1}	Cr, mg kg^{-1}	CO, mg m^{-3}	H_2S, mg m^{-3}	NH_3, mg m^{-3}
1	33.0 ± 4.4	42.5 ± 7.4	1.0 ± 0.1	4.5 ± 0.5	–	–
2	<0.01	202.3 ± 217.6	1.2 ± 0.5	4.3 ± 0.5	0.025 ± 0.005	0.11 ± 0.1
3	33.0 ± 3	42.5 ± 4.4	1.0 ± 0.1	4.3 ± 0.5	0.025 ± 0.005	0.11 ± 0.1
4	–	0.005 ± 0.001	0.2 ± 0.1	3.5 ± 0.5	0.006 ± 0.001	–
MPC	23*	3*	6*	5**	0.008**	0.2**

* Mobile form.

** Maximum single concentration.

See Table 1 notes underneath for symbols. A dash indicates unidentified.

Noise levels were exceeded at plots with high values for road traffic intensity (Table 1).

Intense traffic changes the soil composition and air quality. Therefore, the risk of a toxic impact on plants is increased because of air and soil pollution. Table 2 shows the concentrations of air and soil toxic pollutants along the highways at the testing plots.

Studies related to air pollution revealed that concentrations of most testing substances were within the maximum permissible concentration (MPC). With respect to plots 2 and 3, excess concentrations of hydrogen sulfide were recorded. In addition, concentrations of carbon monoxide were at the upper limit of the MPC. Emissions of ammonia were revealed (Table 2).

The highest copper concentration was recorded in soils in the zones confined to ul. Artyoma (the city's central street). In addition, copper concentrations exceeding MPC (14-fold) were recorded on plots 1 and 3. Within the same zones (plots 1 and 3), there were excess concentrations of zinc. In the zone of Donetsk Botanical Garden arboretum, all of the analyzed values for anthropogenic loads were lower than the MPC values. Therefore, plot 4 is considered a zone of minimum anthropogenic load.

The relationship between the temperature and the elastic modulus were studied with the woody plant shoots sampled on the testing plots. The age of the sampled shoots was 3–5 years. They were cut from the lower part of crowns unshaded during daylight hours at negative temperatures in the dormant period. A thermocaple sensor (TZ-A/BL aluminium model) was put into the samples at the side of cutting at a depth of 1.5 cm to control the temperature of the samples. The cuts were covered by hermetic materials.

The woody tissue modulus of elasticity was determined by the bending angle of a cut branch cylinder horizontally pinched with clamping device as a response to the application of force on its free end (the methods are described in detail in the papers of Kornienko and Netsvetov (2014) and Kornienko et al. (2018)). The modulus of elasticity (MOE) at a temperature of 15°C (the air temperature in the laboratory) was different. Therefore, the values reduced by the value of MOE at $T = 15°C$ were used to compare its temperature dependence. Sampling and studying of the temperature effects on the wood modulus of elasticity (MOE) were performed in February to early March each year (2014–2020).

In order to assess the strength and mechanical stability of silver birch in urban environments, the parameters described below were used. Symbols P_{cr} and m_{cr} denote the maximum permissible load and the mass inducing deformation and failure, H_{cr} denotes a critical trunk height causing irreversible deformation

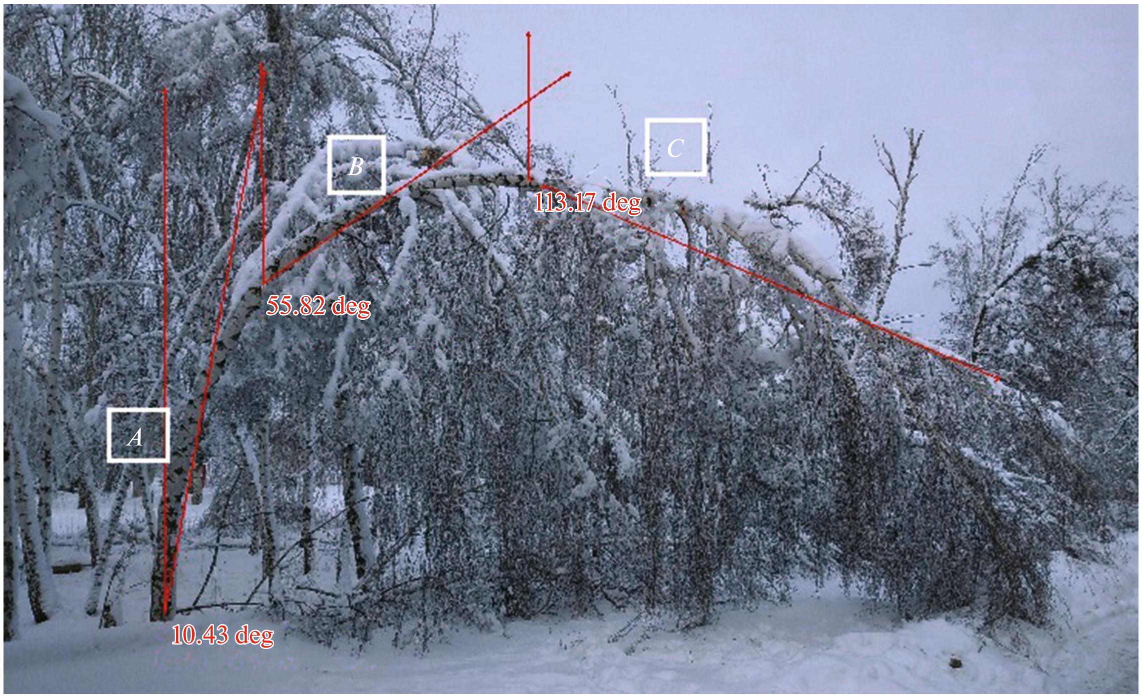

Fig. 1. Angles of divergence from the vertical axis of trunk portions in silver birch trees on experimental plot 1 (a generalised scheme). (*A*) 10.43°, (*B*) 55.85°, and (*C*) 113.17°.

or failure under the trunk weight, *RRB* is the relative resistance to bending, and *EI* is the bending strength (methods are described in detail in the paper of Kornienko and Kalaev (2018)).

The results of visual observations of silver birch trees were shot with a Nikon Coolpix S2600 camera. Images were processed and analyzed using AxioVision Rel. 4.8 software. More than 1500 electron images were processed to study the architectonics of the crown and angles of divergence from the vertical axis of the trunk and skeletal branch portions. The angles were measured with the Measure→Angle functions of the AxioVision Rel. 4.8 software with an accuracy of 1°. The mean parameter value could not demonstrate the complete pattern of woody plant behavior at bending. Therefore, three sites (*A*, *B,* and *C*) separating the plant trunk by bending lines were allocated, indicating the location of growing tree (Fig. 1).

The allometric analyses of the silver birch trunk under the anthropogenic impact were performed on experimental plot 1 in 2016–2017 and 2019–2020. These terms are associated with the weather conditions to produce the data on the architectonics of the crown and the failure rate in silver birch trees. The natural climate conditions described below were recorded in the experiential zone over the indicated years. Thus, the temperature tended to drop to –20°C after long-term warming in the winter season; heavy precipitation (slushy wet snow and snowfall), snowstorms (wind gusts at speeds of 15–20 m/s^{-1}), wet snow sticking, and ice crust covering shoots and trunks were observed.

The tree trunk diameter and height were measured with a tree calliper and the HEC Haglof electronic altimeter (Sweden), respectively. The vital capacity of the analyzed trees was determined with an 8-point grading scale developed by Savelieva (Savelieva, 1975), where 8 grade points correspond to the good health condition, when no dry branch or trunk damage are observed, while the 0 grade point indicates a dried-out tree. The tree ages were determined by Chistyakova (Chistyakova et al., 1989). This method uses symbols for age classes: I, 5–15 years; II, 16–25 years; III, 26–55 years; and IV, 56–75 years. The failure rate for each tree was determined according to the methods provided in the research paper (Kornienko and Prikhodko, 2018). In order to asses the tree stands, methods including visual, retrospective, and instrumental ((a) core incremental sampling to determine the proportion of rot in wood, %; (b) biomechanical testing with the Pullingtest) approaches were used. The woody tissue density (volumetric weight) was estimated with the immersion and weighing method.

Statistica 8 (StatSoft Inc.) and Excel 2010 (Microsoft Corporation) were used for data processing. The regressions were revealed to verify the accuracy of approximations (R^2) upon plotting. The reliability of measurements in differences between the average values for the L : D coefficient and the tree condition (norm, deform, and crushed) were estimated using Student's *t*-test. The Pearson correlation coefficient (*r*), considered different from zero at $p < 0.05$, was used to

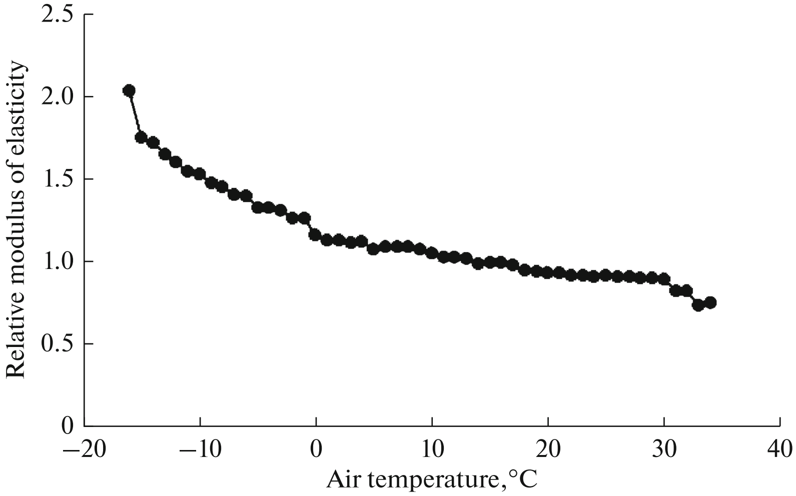

Fig. 2. Temperature effects on relative values for the modulus of elasticity in silver birch woody tissues.

reveal the validity between the L : D coefficient and the mechanical stability.

RESULTS AND DISCUSSION

Silver birch bichemical surveys. The woody tissue density in Donetsk environments is 980 ± 7 kg m^{-3} relative to the location of growing.

The modulus of elasticity under the urban anthropogenic load (experimental plots 1–3) is 5.03 ± 0.77 GL m^{-2}, while it is 4.30 ± 0.46 GL m^{-2} in the Donetsk Botanical Garden (plot 4, arboretum). Differences between variables for the biochemical parameters are significant at $p < 0.05$.

Temperature effects on silver birch woody-tissue MOE in vitro (laboratory surveys). The MOE dependence on temperature in a generated pattern for all specimens tends to a nonlinear drop if there is a temperature increase from 225 to 317 K (Fig. 2).

At thawing temperatures, the wood modulus of elasticity in all of the specimens tends to change unevenly, in stages. The number of breaks of the MOE curve (*T*) varies from 1 to 3, while the temperatures at the angle change as a result of bending MOE (*T*) are in the range of 2°–4°. The greatest curve steepness indicated at a plot is for the value in the range of −16 to 0°C. The experimental data coincide with the datasets produced in the surveys of Japanese researchers A. Mishiro and I. Asano (1984a, 1984b). It should be noted that the variables for the points of bending might vary relative to the plant species properties (for instance, anatomic and biochemical characteristics (Kornienko and Netsvetov, 2014)). With respect to the experiments observed hereby, the specimen temperature and its rate of rise varied over time. The curve steepness of the elastic modulus dependence on the temperature tends to come down along with dropping the rate of a specimen temperature rise. Species differences in this process are not well studied, while they may be revealed, for instance, with the assimilate location in tree resin, which can affect the ice formation in tree vessels.

Upon an uneven thawing temperature (nonlinear dependence, Figs. 3a, 3b), the modulus of elasticity tends to decline at its record rate at the moment, when free water and ice clusters are present, which, in turn, affects the mechanical stability and failure rates of the whole plant. With local heating, the integrity identity of morphological structures is disturbed, when the tree trunk tends to transit from a uniform structure into structural heterogeneity (though phase water transfers in vessels) with a loss of stability. In situ, such effects can be observed upon a shifting of the seasons and nontypical climate conditions during, for instance, winter.

Temperature effects on the mechanical stability of woody plants growing under the anthropogenic impact. The *EI* parameter reflects the woody plant strength to bending, potentially causing the irreversible deformation of a trunk/skeletal branch under the impact of loads of different types. Bending occurs along with bending moments at the trunk/skeletal-branch cross section.

With respect to the silver birch tree, the ratio of *EI* to L : D **follows** a power law ($R^2 = 0.83$). At thawing temperatures, the *EI* parameter decreases by approximately 45%, which can cause the loss of mechanical stability and trunk irreversible deformation (Fig. 4a) under the impact generated with natural-climate factors

The ratio of *RRB* to L : D follows a linear dependence ($R^2 = 0.87$), while the P_{cr}-to-L:D ratio follows a power law ($R^2 = 0.97$). The parameters are closely related to the value for the woody plant modulus of elasticity, depending on the ratio of trunk diameter to its height. The young plants (under 5–7 years old) are most at risk, since they grow suppressed under the effect of a dense tree stand, competing for light as

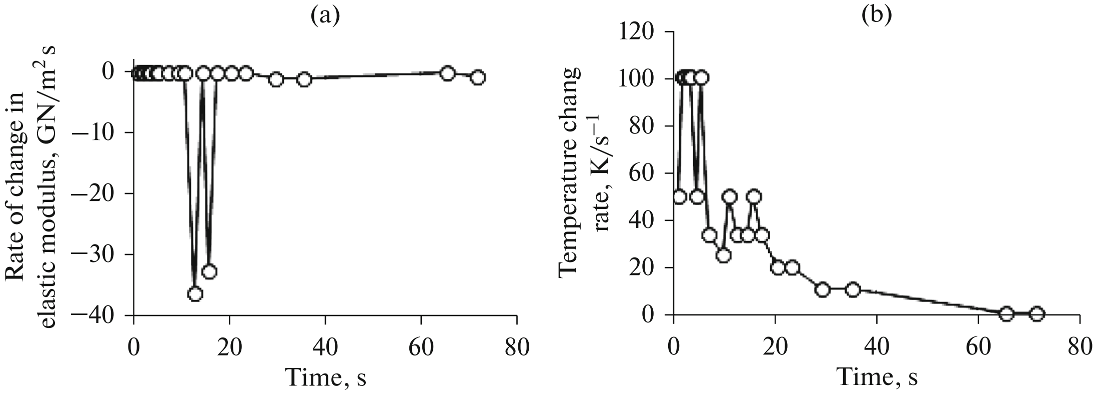

Fig. 3. Effects of the rate of change in temperature on the rate of change in modulus of elasticity in wood over time.

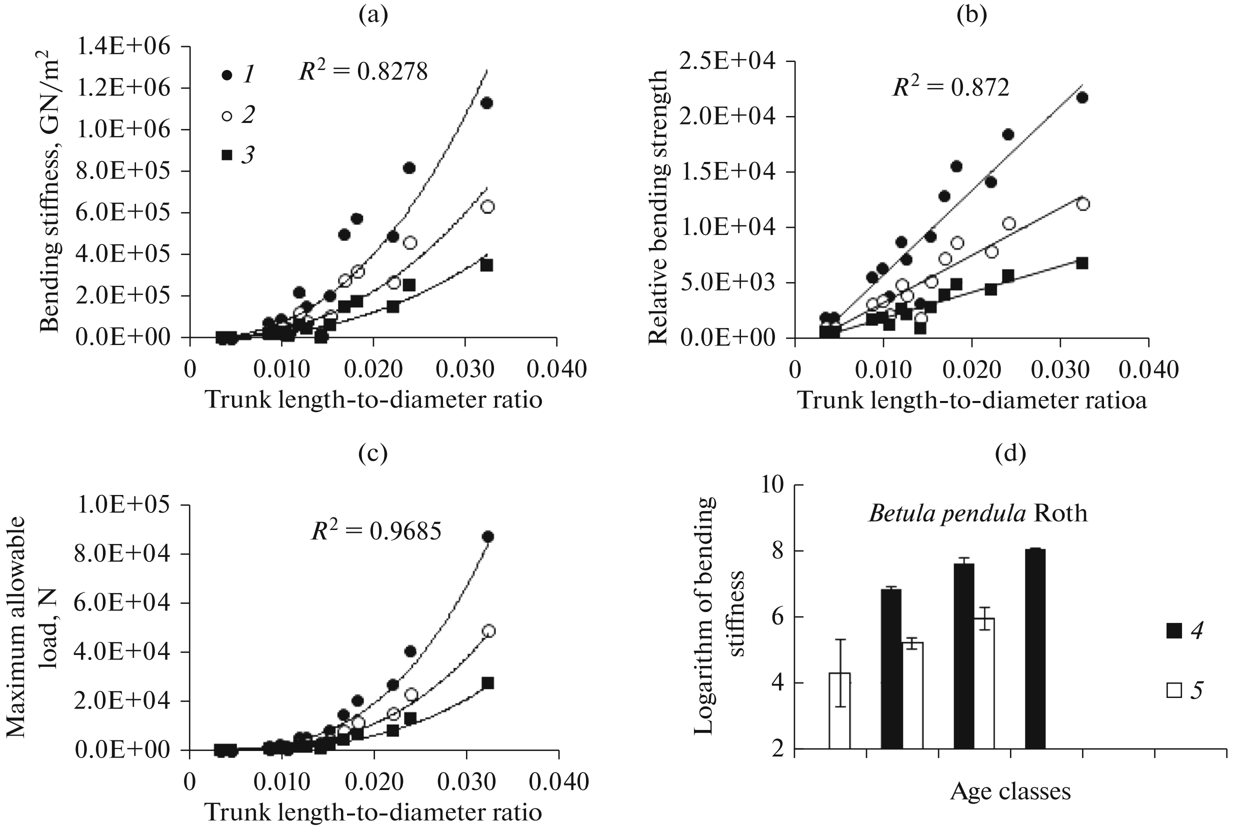

Fig. 4. Dependence of the mechanical stability parameters on the L : D (a–c) ratio and the age classes (d). (*1*) Parameter value for a winter season, (*2*) parameter value at thawing temperature, (*3*) parameter value in a summer season at positive temperatures, (*4*) values produced within the land area of Donetsk Botanical Garden (control), and (*5*) values produced under conditions of anthropogenic impact in Donetsk.

mature plants (with thin and high trunks, L : D < 0.01, Fig. 4b).

The maximum permissible load means there is a precise critical mass causing irreversible changes/trunk breakage (Fig. 4c). The L : D ratio may be used as a morphometric marker for woody plant stability, following the dependence in Fig. 3c. At a L : D ratio in the range of 0.004 to 0.01, the critical mass varies from 11 to 815 kg. In addition, the trunk is in frozen status. Relative to the temperature variance (Figs. 2, 3), the tree mechanical stability decreases by approximately 45% and P_{cr} values are in the range of 6.2 to 458.9 kg. These values can be easily reached in urban environments under the effects of environmental temperature changes and wind and gravity loads.

The temperature dependences of MOE and mechanical stability parameters, obtained within the

Table 3. Influence of the place of growth of a tree stand on the angle of divergence from the vertical axis of the silver birch trunk (2017)

Place of growth	Number, units	Angle of divergence from the vertical axis of the trunk, °			
		$\bar{x} \pm s_x$	percentage of total number, %	MAX	Percentage of total number, %
Tree stand edge extending from the side of a dwelling house	91	16 ± 5	60	43	40
Tree stand edge extending from a highway	220	15 ± 6	40	26	60
Tree stand center	352	4 ± 2	90	12 ± 3	10

See notes to Table 1 for symbols. A dash indicates unidentified.

Table 4. Influence of the place of growth in the tree stand on the angle of divergence from the vertical axis of the silver birch trunk (2020)

Place of growth	Angle of divergence from the vertical axis, ° $\bar{x} \pm s_x$		
	section *A*	section *B*	section *C*
Tree stand edge extending from the side of a dwelling house	18 ± 3	57 ± 7	118 ± 12
Tree stand edge extending from a highway	14 ± 3	49 ± 8	96 ± 21
Tree stand center	7 ± 5	36 ± 26	80 ± 44

See notes to Table 1 for symbols. A dash indicates unidentified.

survey, can explain the effects of silver birch trunk deformation and breakage in the winter season.

Surveys of crown architectonics in silver birch trees growing in Donetsk anthropogenic impact environments in 2017–2020. In the environments of low anthropogenic impact in the arboretum of the Donetsk Botanical Garden, silver birch trees show great vital capacity scored highly (5–7 points for a status rated as good by Savelieva). They were not damaged or bent irreversibly during windfalls (2017–2020), blizzards, or ice storms in 2017 and 2020. This can be explained by the log*EI* dependence on the age (Fig. 4d). Under the relative control, the bending stiffness value is 22 ± 2% higher than that under the urban anthropogenic load ($p < 0.05$). In addition, the angles of divergence from the vertical axis are no more than 5°, while L : D > 0.02.

The surveys of urban silver birch tree plantations under high anthropogenic impact on plot 1 in 2017 revealed that angles of divergence from the vertical axis of trunk portions (their highest values) at the side of a dwelling house were twofold higher than that for birch trees growing on the side of a highway. Practically smooth trunks with small angles of inclination at 2°–6° to the vertical axes could be observed in the middle of the tree stand (Table 3).

The surveys in 2020 revealed that the angle of inclination of plant trunks changed and transformed (Table 4). The parameter average value did not conform to the woody plant behavior at bending yet to describe it adequately. Therefore, three sections separating the plant trunk along the lines of bending were allocated. Sections *A*, *B*, and *C* were determined from the trunk base until first line bending (~3 m), in the middle of the trunk, and along the line bending toward the crown top, respectively.

The maximum bending moments in trunks were observed at the edge of a tree stand. The position of a tree did not tend to change with load removal. Therefore, irreversible deformation may be assumed. Overall, 168 plants were subjected to the snowstorm causing the irreversible deformation.

Impact of seasonal natural climate factors on failure rates in silver birch trees growing under anthropogenic impact. The storm in 2017 tore up several trees, showing divergence angles of 40°–45° to the vertical axis in the first row at the side of a dwelling house. Allometric parameter studies experimentally determined that the L : D coefficient for such trees was ≤0.01.

In 2020, 63 trees were uprooted under the blizzard and freezing rain conditions. Tree breakage was recorded at heights of 2–4 m (35%), 5–6 m (17%), 7–8 m (52%), and 9 m (6%). These trees generally have rather thin trunks. Their L : D comprises 0.01. The dependence of such trees on resistance to bending was estimated with the L : D ratio relative to their condition, rated as normally growing ("norm" trees showing vertical 90° ± 5° degree direction), deformed ("deform"), or with trunk breakage ("crushed") caused by the impact of climate factors (blizzards and freezing rains) (Fig. 5). The ratio of *EI* to L : D for all

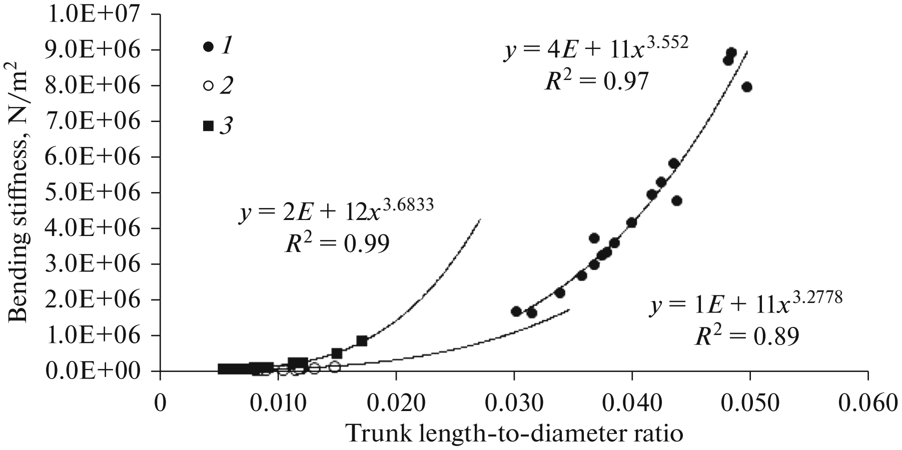

Fig. 5. Dependence of tree-trunk bending strength on the L : D ratio. (*1*) Strictly vertical direction of trunk growth, (*2*) deformed and bent trunks, and (*3*) trunk splits.

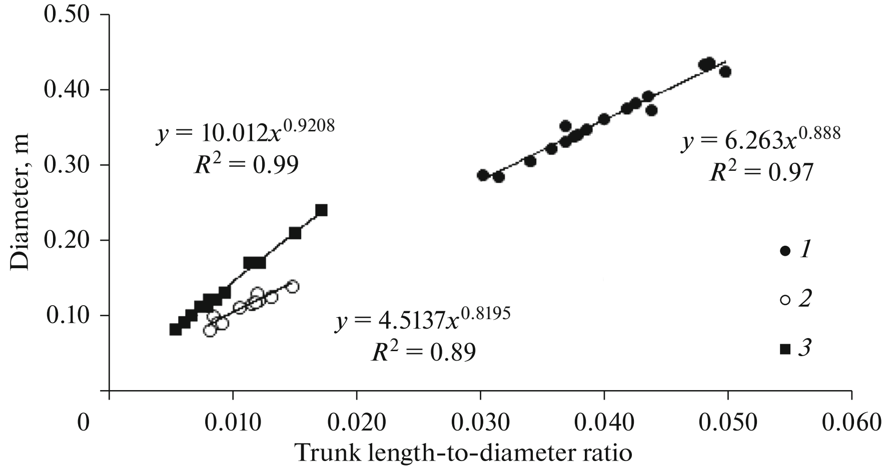

Fig. 6. Dependence of tree trunk diameter on the L : D ratio as a morphometric marker for mechanical stability. (*1*) Strictly vertical direction of trunk growth, (*2*) deformed and bent trunks, and (*3*) trunk splits.

of the tree groups follows a power law and represents a high coefficient of determination, denoted by $R^2 \sim 0.89–0.99$. With respect to the trees growing vertically, the L : D ratio was in the range of 0.03–0.05.

Trees growing under the anthropogenic impact have lower stability, which can be associated with (1) the dendrometric parameters of the trunk (Fig. 6) and (2) the level of biomass produced relative to tree height and, consequently, load effects, such as the wind force and the additional canopy mass saturated by precipitation at the level of the upper third of the tree height. Therefore, the trunk breakage of two types was generally recorded. The breakage of first type is located at a height of 2–4 m (35%), i.e., at the trunk base, caused by heating of the trunk, which resulted in heterogeneous structure formation inducing tension in a mechanically loaded trunk at a height of 2–4 m. The second type of breakage is located at a height of 7–9 m (58% of total number of collapsed trees), i.e., at the upper third of the tree height, which represents the classical ecological strategy of tree survival under the impact of critical static natural climate loads (wet snow sticking and ice crusting).

The L : D **coefficient as a morphometric marker for mechanical stability of silver birch trees in the south of the East European Plain (Donetsk Hill Range).** The relevance of research focused on the relationship between the *d* and *h*(*l*) trunk morphometric parameters and the tree mechanical resistance to wind and gravity loads was noted by G.B. Kofman in his Tree Growth and Form research paper (1986). He used the $h(l) : \mathrm{d} \sim 10^2$ ratio (i.e., the ratio of height : length of a tree trunk to its diameter at the base) to reveal the mechanically stable status of a tree. It was theoretically ascertained that the trees are threatened by a loss of elastic mechanical stability at $h > 110r$ (h is height; r is

Table 5. Relationship between the tree status (failure rate) with its mechanical stability and the L : D coefficient

Tree status	Trunk length-to-diameter ratio, L : D	Bending stiffness, N/m^{-2}
Norm	0.28–0.43	1.59×10^6–8.93×10^6
Deform	0.08–0.015	1.01×10^4–10.49×10^4
Crushed	0.05–0.017	1.01×10^4–8.19×10^5

Norm indicates a strictly vertical direction of trunk growth, Deform indicates deformed and bent trunks, and Crushed indicates trunk splits.

radius at the base). However, the author used physicomechanical parameters (E is modulus of elasticity and ρ is woody tissue density) for industrial (dry) coniferous wood to develop the mathematical model describing the living tree stability, which should not be done in to the opinions of other researchers (Burgert et al., 2001). Thus, dry wood showing high rigidity and fragility is substantially different from green living wood, which is more elastic (relative to elastic modulus correlating with water content (w)) and less brittle (Burgert et al., 2001). In addition, the individual adaptation of woody species to the environmental conditions of growth is a significant factor for mechanical resistance to the impact of natural climate factors (Thomas, 2011). Therefore, it cannot be correct to use the estimates performed with plants of the same species unrelated to the environmental conditions of growth and the physicomechanical properties of living plant wood. Moreover, it is ineffective to use them as both the universe models for the mechanical behavior of a tree under load impacts and the datasets to calculate the morphometric coefficient of stability/failure rates (Niklas and Spatz, 2012; Albrecht et al., 2016). Consequently, current tasks include finding the relationships between the status (failure) with mechanical stability and the L : D coefficient for each woody plant species and determining the extent of the variance for this relationship relative to the environmental conditions of growth.

The survey revealed a strong positive correlation between the morphometric L : D coefficient and the mechanical stability ($r = 0.87$) and failure rates ($r = 0.79$) for silver birch trees during statistical data processing with the correlation analysis method (Table 5).

The L : D ratio for silver birch trees growing under the impact of anthopogenic loads in Donetsk comprised, on average, 0.01 ± 0.003. At such values, irreversible deformations or breakage were observed. This may be explained by the fact that disorders in physiological–biochemical, cellular, molecular, and genetic processes occur in a plant under the anthopogenic impact (Polyakov, 2009; Alonso-Serra et al., 2020). The outcomes of pollution represent changes in the morphometric parameters for woody plant trunks and crowns (Polyakov, 2009). It is considered that morphometric parameters for woody plant trunks and crowns contribute to variations in tree mechanical stability and failure rates (Sellier and Fourcaud, 2009). Therefore, it seems possible to use the L : D coefficient as a morphometric marker for the mechanical stability of silver birch trees in the environments in the south of the East European Plain (Donetsk Hill Ridge). In addition, the relationship between the L : D variance at 0.01 and the tree status tends to be evident for the other plant species. This parameter may be universal. However, it requires the further research.

CONCLUSIONS

The temperature effect on the the elasticity modulus of wood tissues in a silver birch tree was revealed. This parameter reliably decreases, on average, 2–2.5 times at thawing temperatures.

MOE decreases unevenly, in stages. The rate of elastic-modulus change (dMOE:dt) relative to the rate of woody-plant specimen/trunk thawing (dT:dt) has the greatest effect on the mechanical stability of a tree.

The mechanical stability parameters tend to fall by 45%, on average, at thawing temperatures.

These changes affect the angles of divergence from the vertical axis of the trunk portions, the angles of its skeletal branch attachment, bending strength, and tree resistance to wind and gravity loads. Under low anthropogenic impact, the logEI mechanical stability value for plants at the age of 40–45 years is 22 ± 2% higher than that under a higher anthropogenic load in cities ($p < 0.01$). Under the effects of anthropogenic and wind loads, temperatures, and snow and ice storm conditions, the transformation of architectonics of the silver birch crown occurs. These changes cause irreversible deformations or trunk breakage under blizzards and freezing rain. Therefore, 168 woody plants underwent a process of irreversible deformation causing a high failure rate. In addition, 63 trees were uprooted. Splits were recorded in plants at heights of 2–4 m (35%), 5–6 m (17%), 7–8 m (52%) and 9 m (6%).

Correlation analysis revealed a strong positive relationship between the L : D morphometric coefficient and mechanical stability ($R = 0.87$), along with the the failure rate ($R = 0.79$) in silver birch trees. In this regard, it seems possible to use the L : D coefficient as a morphometric marker for mechanical stability in silver birch trees in the south of the European Plain (Donetsk Hill Ridge).

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interests.

REFERENCES

Albrecht, A., Badel, E., Bonnesoeur, V., Brunet, Y., Constant, T., Defossez, P., Langre, E., Dupont, S., Fournier, M., Gardiner, B., Mitchell, S.J., Moore, J.R., Moulia, B., Nicoll, B.C., Niklas, K.J., Schelhaas, M., Spatz, H.-Ch., and Telewski, F.W., Comment on “Critical wind speed at which trees break”, *Phys. Rev.*, 2016, vol. 94, pp. 067001-1–067001-2.

Alonso-Serra, J., Shi, X., Peaucelle, A., Rastas, P., Bourdon, M., Immanen, J., Takahashi, J., Koivula, H., Eswaran, G., Muranen, S., Help, H., Smolander, O., Su, Ch., Safronov, O., Gerber, L., Salojarvi, J., Hagqvist, R., Mähönen, A., Nieminen, K., and Helariutta, Y., Elimäki locus is required for vertical proprioceptive response in birch trees, *Curr. Biol.*, 2020, vol. 30, no. 4, pp. 589–599.

Burgert, I., Bernasconi, A., Niklas, K.J., and Eckstein, D., The influence of rays on the transverse elastic anisotropy in green wood of deciduous tree, *Holzforschung*, 2001, vol. 55, no. 5, pp. 449–454.

Chistyakova, A.A., Zaugol’nova, L.B., Poltinkina, I.V., Kut’ina, I.S., and Lshtsinskii, N.N., *Diagnozy i klyuchi vozrastnykh sostoyanii lesnykh rastenii. Derev’ya i kustarniki* (The Keys to Diagnosis of the Age State of Forest Plants. Trees and Shrubs), Moscow: Prometei, 1989.

Curtis, P.S. and Gough, C.M., Forest aging, disturbance and the carbon cycle, *New Phytol.*, 2018, vol. 219, pp. 1188–1193.

Dahle, G.A. and Grabosky, J.C., Variation in modulus of elasticity (*E*) along *Acer platanoides* L. (Aceraceae) branches, *Urban For. Urban Greening*, 2010, vol. 9, pp. 227–233.

Dahle, G.A., James, K.R., Kane, B., Grabosky, J.C., and Detter, A., A review of factors that affect the static load-bearing capacity of urban trees, *Arboric. Urban For.,* 2017, vol. 43, no. 3, pp. 89–106.

Fahey, R.T., Atkins, J.W., Campbell, J.L., Rustad, L.E., Duffy, M., Driscoll, Ch.T., Fahey, T.J., and Schaberg, P.G., Effects of an experimental ice storm on forest canopy structure, *Can. J. For. Res.*, 2020, vol. 50, no. 2, pp. 136–145.

Fournier, M., Dlouhá, J., Jaouen, G., and Almeras, T., Integrative biomechanics for tree ecology: beyond wood density and strength, *J. Exp. Bot.*, 2013, vol. 64, no. 15, pp. 4793–4815.

Glukhov, A.Z., Kharkhota, L.V., Pasternak, G.A., and Likhatskaya, E.N., Current state of Donetsk dendroflora, *Samar. Nauchn. Vestn.* 2016, vol. 2, no. 15, pp. 20–24.

Green, D.W., Evans, J.W., Logan, J.D., and Nelson, W.J., Adjusting modulus of elasticity of lumber forchanges in temperature, *For. Prod. J.*, 1999, vol. 49, no. 10, pp. 82–94.

James, K.R., Haritos, N., and Ades, P.K., Mechanical stability of trees under dynamic loads, *Am. J. Bot.*, 2006, vol. 93, no. 10, pp. 1522–1530.

James, K.R., Dahle, G.A., Grabosky, J., Kane, B., and Detter, A., Tree biomechanics literature review: dynamics, *Arboric. Urban For.,* 2014, vol. 40, no. 1, pp. 1–15.

Jelonek, T., Tomczak, A., Karaszewski, Z., Jakubowski, M., Arasimowicz-Jelonek, M., Grzywiński, W., Kopaczyk, J., and Klimek, K., The biomechanical formation of trees, *Drewno*, 2019, vol. 62, no. 204, pp. 5–22.

Klein, R.W., Koeser, A.K., Kane, B., Landry, S.M., Shields, H., Lloyd, S., and Hansen, G., Evaluating the likelihood of tree failure in Naples, Florida (United States) following hurricane Irma, *Forests*, 2020, vol. 11, no. 485, pp. 1–10.

Kofman, G.B., *Rost i forma derev’ev* (Growth and Form of Trees), Novosibirsk: Nauka, 1986.

Kornienko, V.O. and Kalaev, V.N., *Mekhanicheskaya ustoichivost’ drevesnykh porod i rekomendatsii po predotvrashcheniyu ikh avariinosti v gorodskikh nasazhdeniyakh* (Mechanical Stability of Tree Species and Recommendations for Preventing their Accident Rate in Urban Plantings), Voronezh: Roza Vetrov, 2018.

Kornienko, V.O. and Netsvetov, M.V., The influence of negative temperatures on the mechanical resistance of red oak (*Quercus rubra* L.), *Prom. Bot.*, 2013, vol. 13, pp. 180–186.

Kornienko, V.O. and Netsvetov, M.V., Cryoscopy of wood moisture and temperature dependence of wood elasticity modulus, *Visti Biosf. Zapovid. “Askaniya-Nova”*, 2014, vol. 16, pp. 88–94.

Kornienko, V.O., Netsvetov, M.V., Nikulina, V.M., and Suslova, O.P., Investigation of the trees’ endurance for vibrations, *Visn. L’vivs’kogo Univ. Ser. Fiz.*, 2009, no. 44, pp. 185–193.

Kornienko, V.O., Kalaev, V.N., and Elizarov, A.O., The influence of temperature on biomechanical properties of woody plants in the conditions of protected and open grounds, *Sib. Lesn. Zh.*, 2018, no. 6, pp. 91–102.

Mikheeva, M.A. and Fedorova, A.I., Effect of high temperatures on the stability of trees in urban environments, *Vestn. Voronezh. Gos. Univ., Ser.: Geogr. Geoekol.*, 2011, no. 2, pp. 166–175.

Mishiro, A. and Asano, I., Mechanical properties of wood at low temperatures: effect of moisture content and temperature on bending properties of wood. Part I. Moisture content below the fiber saturation point, *J. Jpn. Wood Res. Soc.*, 1984a, vol. 30, no. 3, pp. 207–213.

Mishiro, A. and Asano, I., Mechanical properties of wood at low temperatures: effect of moisture content and temperature on bending properties of wood. Part II. Moisture content beyond the fiber saturation point, *J. Jpn. Wood Res. Soc.*, 1984b, vol. 30, no. 4, pp. 277–286.

Netsvetov, M.V. and Suslova, E.P., Mechanical stability of trees and schrubs under vibration loads, *Prom. Bot.*, 2009, no. 9, pp. 60–67.

Netsvetov, M.V., Suslova, E.P., Nikulina, V.M., and Kornienko, V.O., Mechanical resistance of trees to anthropogenic vibration loads, in *Program and Proceedings of II International Conference, Lviv–Vorokhta, Ukraine “Physical Methods in Ecology, Biology and Medicine”*, Lviv: Vidavnichii Tsentr LNU im. I. Franka, 2019, pp. 22–23.

Neverova, O.A., Legoshchina, O.M., and Bykov, A.A., Anatomy of leaves of *Betula pendula* (Roth.) affected by air emissions in industrial area of Kemerovo city, *Middle East J. Sci. Res.*, 2013, vol. 17, no. 3, pp. 354–358.

Niklas, K.J. and Spatz, H.-C., Worldwide correlations of mechanical properties and green wood density, *Am. J. Bot.*, 2010, vol. 97, no. 10, pp. 1587–1594.

Niklas, K.J. and Spatz, H.-Ch., *Plant Physics*, Chicago: University of Chicago Press, 2012.

Nocetti, M., Brunetti, M., and Bacher, M., Effect of moisture content on the flexural properties and dynamic modulus of elasticity of dimension chestnut timber, *Eur. J. Wood Wood Prod.*, 2015, vol. 73, pp. 51–60.

Nock, C.A., Lecigne, B., Taugourdeau, O., Greene, D.F., Dauzat, J., Delagrange, S., and Messier, Ch., Linking ice accretion and crown structure: towards a model of the effect of freezing rain on tree canopies, *Ann. Bot.*, 2016, vol. 117, no. 7, pp. 1163–1173.

Polyakov, A.K., *Introduction of woody plants in a technogenic environment*, Donetsk: Noulidzh, 2009.

Razdorskii, V.F., *Arkhitektonika rastenii* (Plant Architectonics), Moscow: Sov. Nauka, 1955.

Sarbaeva, E.V., Voskresenskaya, O.L., and Voskresenskii, V.S., Assessment of the resistance of trees and shrubs in an urban environment, *Sovrem. Probl. Nauki Obraz.*, 2013, no. 2. http://science-education.ru/ru/article/view?id=9011. Cited April 27, 2020.

Savel'eva, L.S., *Ustoichivost' derev'ev i kustarnikov v zashchitnykh lesnykh nasazhdeniyakh* (Resilience of Trees and Shrubs in Protective Forest Stands), Moscow: Lesn. Prom-st., 1975.

Sell, J., *Eigenschaften und Kenngrößen von Holzarten*, Lignum: Baufachverlag AG Zürich, 1989.

Sellier, D. and Fourcaud, T., Crown structure and wood properties: influence on tree sway and response to high winds, *Am. J. Bot.*, 2009, vol. 96, no. 5, pp. 885–896, https://doi.org/10.3732/ajb.0800226

Spatz, H.-C. and Pfisterer, J., Mechanical properties of green wood and tree risk assessment, *Arboric. Urban For.,* 2013, vol. 39, no. 5, pp. 218–225.

Suslova, O.P., Polyakov, O.K., Netsvetov, M.V., Dats'ko, O.M., and Likhats'ka, O.M., Viability of woody plants in urban street stands in the South-East of Ukraine, *Prom. Bot.*, 2012, vol. 12, pp. 12–18.

Szmutku, M.B., Campean, M., Sand Andu, A.V., Microstructure modifications induced in spruce wood by freezing, *Pro Ligno*, 2011, vol. 7, no. 4, pp. 26–31.

Szmutku, M.B., Campean, M., and Laurenzi, W., Influence of cyclic freezing and thawing upon spruce wood properties, *Pro Ligno*, 2012, vol. 8, no. 1, pp. 35–43.

Thomas, S.C., Size- and age-related changes in tree structure and function, *Tree Physiol.*, 2011, vol. 2, pp. 33–64.

Virot, E., Ponomarenko, A., Dehandschoewercker, E., Quere, D., and Clanet, C., Critical wind speed at which trees break, *Phys. Rev.*, 2016, vol. 93, pp. 023001-1–023001-7.

Wood handbook: Wood as an Engineering Material, Madison: U. S. Dep. *Agric., For. Serv.*, Forest Products Laboratory, 1999.

Wood handbook: Wood as an Engineering Material, Madison: Forest Products Laboratory, 2010.

Zelinka, S.L., Stone, D.S., and Rammer, D.R., Equivalent circuit modeling of wood at 12% moisture content, *Wood Fiber Sci.*, 2007, vol. 39, no. 4, pp. 556–565.

Translated by O. Zhiryakova